ADDITIVE MANUFACTURING APPLIED TO UNDERWATER COMPONENTS: A SYSTEMATIC REVIEW

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Abstract: Additive manufacturing (AM) has garnered significant attention due to its potential and advantages, particularly in the context of underwater environments. This study aims to identify articles describing the 3D printing of components applied in underwater environments. A systematic literature review was conducted on the Web of Science and Scopus databases regarding the proposed topic. After searching and applying inclusion and exclusion criteria, 15 most relevant articles were selected. Most of the articles focused on printing housings and propellers for Autonomous Underwater Vehicle (AUV), using Material Extrusion (MEX) technology and polymers as the printing material. The study provides insights into the potential of AM for the underwater industry, such as new design, and efficient production methods.

Keywords: Additive manufacturing, underwater environment, systematic review.

MANUFATURA ADITIVA APLICADA EM COMPONENTES SUBAQUÁTICOS: UMA REVISÃO SISTEMÁTICA

Resumo: A manufatura aditiva (MA) tem se destacado pelo seu potencial e vantagens, especialmente no contexto de ambientes subaquáticos. Este estudo tem o objetivo de identificar artigos que descrevem a fabricação 3D de componentes aplicados em ambiente subaquático. Uma revisão sistemática da literatura foi feita na base de dados *Web of Science* e *Scopus* sobre o tema proposto. Após pesquisa e aplicação dos critérios de inclusão e exclusão, foram selecionados 15 artigos mais relevantes. A maioria dos selecionados focou na impressão de carcaças e propulsores de veículos submarinos autônomos, pela tecnologia de *Material Extrusion (MEX)* e polímeros como material de impressão. O estudo fornece novas percepções sobre o potencial da MA para a indústria subaquática.

Palavras-chave: Manufatura aditiva, ambiente subaquático, revisão sistemática.

1. INTRODUCTION

Additive manufacturing (AM), also known as 3D printing or rapid prototyping, has garnered increasing interest for its captivating potentialities and numerous advantages. It enables direct fabrication of models from three-dimensional Computer-Aided Design (3D CAD) systems. Unlike conventional processes, AM builds products from the bottom up, layer by layer, facilitating the production of intricate and complex objects while overcoming traditional limitations. This versatile technology accommodates a wide range of materials, including metals, thermoplastics, ceramics, and composites, depending on the machine's capabilities. Additive manufacturing offers new possibilities for the industry and the development of innovative products. It enables the integration of multiple components into a single part through generative architecture, reducing the need for downstream assembly and Lightweight [1], [2].

Additive manufacturing can be employed for rapid prototyping, creating conceptual models, low-volume production, and fabricating single and customized parts. AM has also revolutionized assembly simplification and enabled the mass reduction of components. Notably, it has paved the way to produce personalized items, such as dental implants and specialized tools, tailored to individual needs [3].

The naval industry encompasses various sectors with high demand for products and services, and AM offers promising potential to revolutionize this area. AM provides opportunities for innovative solutions, granting greater design freedom and improved performance for underwater components in this industry. However, the application of additive manufacturing in underwater environments presents several challenges. Designing underwater components requires consideration of specific requirements for pressure and corrosion resistance due to extreme conditions. Additionally, the materials used in additive manufacturing may not be approved for underwater use, limiting their applications in hostile marine environments. Consolidated studies and practical experiences are lacking, and rigorous testing is required to validate and certify parts for underwater use. Despite these obstacles, additive manufacturing can aid in creating prototypes and innovative solutions for underwater applications, streamlining the design process and reducing production costs and time. Further research is crucial to advancing the safe and efficient use of additive manufacturing in underwater environments [4], [5].

In the context of the naval industry and its increasing interest in utilizing additive manufacturing for underwater applications, this work aims to identify articles describing the 3D printing of components applied in underwater environments. The systematic literature review focused on articles related to the topic and identified the AM technologies and materials employed, as well as the 3D printed components in underwater applications.

2. METHODOLOGY

The methodology utilized in this study conducts a systematic review of relevant literature from additive manufacturing applied in underwater environments. The research process was carried out the *Web of Science* and *Scopus* databases until June 6th, 2023, with a focus on articles as the publication type. The search criteria targeted article titles, abstracts, and keywords using specific search strings as presented in Table 1. This study was limited on the top 20 most cited and 20 most relevant articles according to each repository's criteria.

Table 1. Keywords and strings applied on the Web of Science and Scopus platform for article selection.

Theme	Keywords
Additive Manufacturing applied in underwater environments	("under water" OR “underwater" OR "subsea" OR "sub sea") AND ("3d print" OR "additive manufacturing" OR "3d printing")

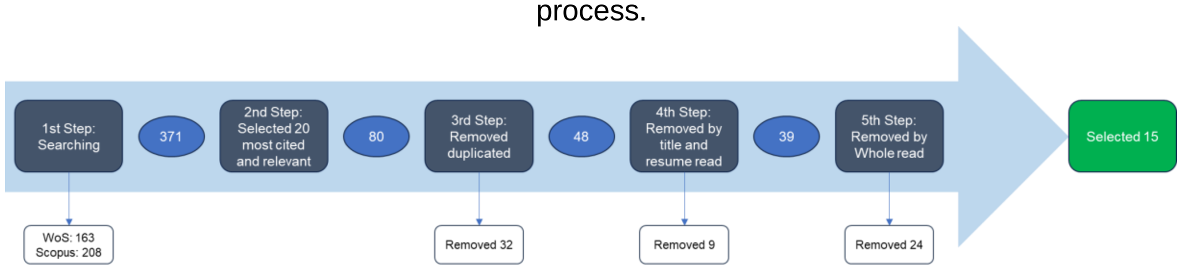
After performing searches in both databases, the initial step involved eliminating duplicate articles from a total of 80. Subsequently, a preliminary selection was made from reading of the titles and abstracts of each article, identifying articles closer to the theme. In the next stage, a more detailed analysis was conducted by reviewing the selected articles in their entirety. During this process, relevant information, such as the printed components, specific additive manufacturing technologies employed, and the AM process used, was collected. Articles without a focus on additive manufacturing for subsea component fabrication were excluded in all steps of selection.

The VOSviewer software was utilized to conduct graphical analyses, facilitating the identification of frequently used terms and their interrelationships within the selected literature. Finally, the study provided a summary of the selected articles, emphasizing the benefits of utilizing additive manufacturing in underwater environments.

3. RESULTS AND DISCUSSION

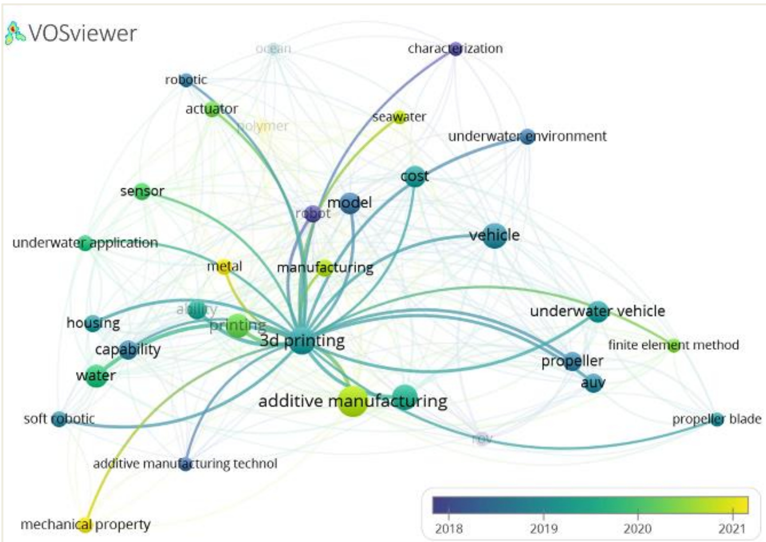
The literature search using the keyword combination related AM and underwater environment returns a total of 371 results. From these results, the top 20 most cited and 20 most relevant articles were selected from each repository, totaling 80 articles. After eliminating duplicates, 48 articles remained for further consideration through title and abstract screening. Following this initial screening, 39 articles were chosen for full-text reading. Finally, 11 articles were deemed highly relevant to the present topic. Figure 1 illustrates all the steps involved in the selection of these relevant articles, outlining the stages of identification, selection, eligibility, and inclusion in the study.

Figure 1. Flowchart illustrating the steps of the article identification, selection, and eligibility process.



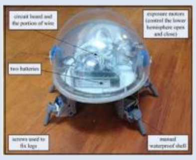
To perform a comprehensive analysis of the relationship between AM and underwater environment, a co-occurrence network was generated using *VOSviewer* software, utilizing metadata from the 45 articles identified in pre-filtering stage. The co-occurrence network graph is presented in Figure 2. The connections between terms in the network represent their relationships, while the size of each circle indicates the frequency of the term appearing in the title, abstract, and keywords. The color-coded representation of each term in the co-occurrence network signifies its temporal relevance, with yellow denoting recent references and dark blue signifying older references in the literature. The term "*additive manufacturing*" is highlighted and found to be connected to other terms such as "*underwater environment*", "*seawater*", "*propeller*" and "*underwater vehicle*". The majority of the interesting terms are recent, ranging between 2018 (dark blue) and 2021 (yellow).

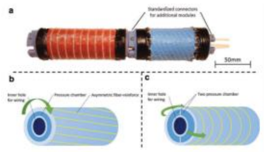
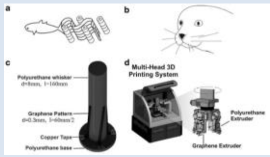
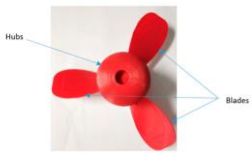
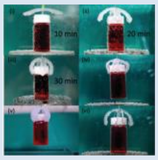
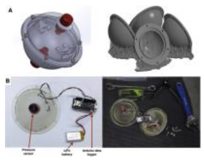
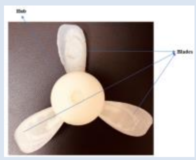
Figure 2. Co-occurrence network analysis of key terms in additive manufacturing for green hydrogen production: a visual exploration.



Additionally, Table 2 presents a comprehensive list of the selected articles, emphasizing the printed components fabricated using additive manufacturing and the corresponding technologies utilized.

Table 2. List of articles and respective component printed by additive manufacturing.

#	3D printing application	AM Process	Material	Figure	Reference
1	Structure of Amphibious Spherical Robot	not mentioned	Acrylonitrile Butadiene Styrene (ABS)		[6]
2	Sensors Housing	Material Extrusion (MEX)	ABS and Polylactic Acid (PLA)		[7]

#	3D printing application	AM Process	Material	Figure	Reference
3	Design of Autonomous Underwater Vehicle (AUV)	Material Extrusion (MEX)	PLA		[8]
4	Underwater vehicles	Material Extrusion (MEX)	PLA, ABS, PLA + Polyurethane, Resine		[9]
5	Robot Arm and gear	Robot arm - Selective laser sintering (SLS) Gear - Direct Metal Laser Sintering (DMLS)	SLS - PA 2200 DMLS - Stainless steel GP1		[10]
6	Soft actuators	not mentioned	Silicone		[11]
7	Fish fin and whisker sensor	Material Extrusion (MEX)	Polyurethane (PU), graphene		[12]
8	AUV propeller	Material Extrusion (MEX)	ABS		[4]
9	Soft actuators with a shape memory hydrogel (SMG)	Stereolithography (SLA)	SMG70-SA30 SMG90-SA10		[13]
10	Housing	Stereolithography (SLA)	Resin		[14]
11	AUV propeller	Material Extrusion (MEX)	Nylon 6		[15]
12	AUV propeller	Material Extrusion (MEX)	Nylon 6, ABS, PLA		[16]

#	3D printing application	AM Process	Material	Figure	Reference
13	Pressure Enclosures	Stereolithography (SLA)	Resin		[17]
14	Sensor housing	Stereolithography (SLA)	Resin		[18]
15	Soft jellyfish robot	Material Extrusion (MEX)	Thermoplastic polyurethane (TPU 92A)		[19]

Additive manufacturing is predominantly utilized for printing housings and propellers, with MEX being the most common technology and polymer as the predominant material. Metal was used in only one instance, specifically for printing a unique component [10].

One aspect found in some articles is the incorporation of bioinspired designs based on marine life for developing their structure [8], [12], [13], [18], [19]. By mimicking nature's efficient and adapted solutions researchers aim to optimize the performance and functionality of the underwater components. However, it is essential to continue validating these bioinspired designs through comprehensive real-world testing to ensure their practicality and suitability for actual underwater use.

The challenges in additive manufacturing for underwater components are multifaceted. On one hand, new rapid prototyping techniques have revolutionized the production of low-cost, flexible hull designs, opening up possibilities for innovative marine structures with improved performance and adaptability. However, one significant challenge lies in addressing water absorption issues that could compromise the integrity and durability of printed components. To mitigate this, researchers have employed polyurethane coatings on the hull, effectively safeguarding against water ingress and ensuring the long-term reliability of the underwater components. These advancements underscore the ongoing efforts to overcome technical obstacles and establish additive manufacturing as a viable and robust solution for underwater applications, providing enhanced design options and improved resilience in challenging aquatic environments.

4. CONCLUSION

This study conducted a comprehensive systematic literature review, highlighting the diverse applications of AM for underwater use. The technology's potential for enhancing design freedom, optimizing performance, and enabling cost-effective production methods has been demonstrated through numerous case studies and research findings. Despite the challenges of material, real-world validation, and design complexity, the innovative approaches, such as bioinspired designs and novel hull construction techniques, offer promising solutions to overcome these obstacles.

The use of additive manufacturing has proven to be a valuable tool for rapid prototyping and concept validation and opens up new opportunities for innovation. the industry is moving closer to realizing the transformative impact of this technology in underwater applications, enabling more efficient, cost-effective, and innovative solutions for the exploration and utilization of underwater resources. Future research could explore advanced materials and new additive manufacturing technologies.

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